# Goal neglect, fluid intelligence and processing speed

**Citation for published version:**
Iveson, MH, Della Sala, S, Anderson, M & MacPherson, SE 2017, 'Goal neglect, fluid intelligence and processing speed: Manipulating instruction load and inter-stimulus interval', *Acta Psychologica*, vol. 176, pp. 1-10. https://doi.org/10.1016/j.actpsy.2017.03.003

**Digital Object Identifier (DOI):**
10.1016/j.actpsy.2017.03.003

**Link:**
Link to publication record in Edinburgh Research Explorer

**Document Version:**
Peer reviewed version

**Published In:**
Acta Psychologica

# Goal neglect, fluid intelligence and processing speed: Manipulating instruction load and inter-stimulus interval.

Matthew H. Iveson[ab], Sergio Della Sala[a], Mike Anderson[c], and Sarah E. MacPherson[a]

[a]Human Cognitive Neuroscience, Department of Psychology, and Centre for Cognitive Ageing and Cognitive Epidemiology, University of Edinburgh, UK

[b]Laboratory of Experimental Psychology, Suor Orsola Benincasa University, Italy

[c]School of Psychology and Exercise Science, Murdoch University, Australia

Abstract: 208 words

Word count: 9333 words

Address correspondence to:

Matthew H. Iveson
Department of Psychology, The University of Edinburgh,
7 George Square, Edinburgh, EH8 9JZ, UK
Tel: 0131 6504005
E-mail: Matthew.Iveson@ed.ac.uk

## Abstract

Goal maintenance is the process where task rules and instructions are kept active to exert their control on behavior. When this process fails, an individual may ignore a rule while performing the task, despite being able to describe it after task completion. Previous research has suggested that the goal maintenance system is limited by the number of concurrent rules which can be maintained during a task, and that this limit is dependent on an individual's level of fluid intelligence. However, the speed at which an individual can process information may also limit their ability to use task rules when the task demands them. In the present study, four experiments manipulated the number of instructions to be maintained by younger and older adults and examined whether performance on a rapid letter-monitoring task was predicted by individual differences in fluid intelligence or processing speed. Fluid intelligence played little role in determining how frequently rules were ignored during the task, regardless of the number of rules to be maintained. In contrast, processing speed predicted the rate of goal neglect in older adults, where increasing the presentation rate of the letter-monitoring task increased goal neglect. These findings suggest that goal maintenance may be limited by the speed at which it can operate.


Keywords: goal neglect; fluid intelligence; processing speed; attention; cognitive aging

## Introduction

Goal maintenance is the ability to keep task-relevant rules and instructions active and accessible in working memory while performing a task, so that they may control and guide appropriate behavior. Goal neglect occurs when these rules and instructions are ignored, despite the task requirements being clearly understood and kept in mind. The phenomenon of goal neglect has been reported in patients with lesions in the frontal lobes (Duncan, Burgess, & Emslie, 1995; Luria, 1966; Milner, 1963) but also in healthy individuals (Altamirano, Miyake, & Whitmer, 2010; Duncan, Emslie, Williams, Johnson, & Freer, 1996; Duncan et al., 2008; Piek et al., 2004; Towse, Lewis, & Knowles, 2007). It manifests as an overall difficulty obeying novel rules (e.g., Duncan, Schramm, Thompson, & Dumontheil, 2012) or a failure to correctly complete the task (Duncan et al., 1996).

Goal neglect has been considered to be the result of over-taxing a limited capacity system reliant on working memory (Kane & Engle, 2003; Duncan et al., 2008). The nature of this limitation has been investigated in several ways. Using a Stroop task, Kane and Engle (2003) have shown that the goal maintenance system is limited by the amount of competition between rules that it can control at any one time. When a greater proportion of congruent compared to incongruent color-ink trials are presented, the word-naming goal provides too much competition for the color-naming goal. The resulting neglect of the color-naming goal is problematic during incongruent trials, as only color-naming responses are correct (see also Morey, Elliott, Wiggers, Eaves, Shelton, & Mall, 2012). In contrast, using a letter- and number-monitoring task, Duncan et al. (2008, Experiment 3), have shown that the goal maintenance system is limited in the number of rules that it can keep active at any one time. Participants were presented with two subtask blocks – one in which pairs of letters appeared and one in which pairs of numbers appeared. Each subtask had specific instructions, requiring participants to either report letters or to sum numbers while only attending to one side of the pair. The relevant side was indicated by one cue presented at the start of the trial sequence and one cue presented near the end of the trial sequence. A mismatch in the direction indicated by the first and the second side cues would require participants to switch sides during the trial (e.g., first cue: watch right, second cue: watch left). Goal neglect was observed as a tendency to ignore the second cue when it indicated a switch and continue to respond to the stimuli on the initial side. Duncan et al. (2008) reported that this failure to follow the second side cue was more frequent if participants received instructions for both the letter- and number-subtask blocks at the start of the experiment, rather than receiving the relevant instructions at the beginning of each subtask. Increasing the number of instructions to be maintained increased the load placed on the goal maintenance system, and led to frequent neglect of a specific task rule.

Research has attempted to identify the cognitive abilities associated with goal neglect under high goal maintenance demands. In the letter- and number-monitoring task, Duncan et al. (2008) reported that the tendency to neglect the side-relevant task rules when more instructions had to be maintained (i.e., instruction load effects) was more prominent in individuals from the lower-end of the general fluid intelligence (gF) distribution. As a result, Duncan et al. proposed that gF supports the ability to maintain and follow a larger set of complex task rules, with high levels of gF resulting in improved goal maintenance abilities. This effect of introducing additional irrelevant instructions, and its association with gF, has since been demonstrated in other complex tasks (e.g., Roberts, Jones, Davis, Ly, & Anderson, 2014; Roberts & Anderson, 2014; Bhandari & Duncan, 2014).

Despite the reported association between the ability to deal with more instructions and gF, there has been little consideration of the role that other cognitive factors might play in goal neglect. One such factor is processing speed. Processing speed is a general cognitive factor which has been implicated in a wide range of complex behaviors (e.g., Salthouse, 2005; Johnson & Deary, 2011), such as the fast and efficient use of color-word instructions in the Stroop task (e.g., Salthouse & Meinz, 1995). In terms of goal maintenance, it is possible that enacting the relevant task goal (and avoiding goal neglect) depends on the speed at which the goal maintenance system can alter the attentional bias afforded to particular rules (Notebaert, Gevers, Verbruggen, & Liefooghe, 2006; Sharma, Booth, Brown, & Huguet, 2010). As gF and processing speed are strongly correlated (e.g., Jensen, 2006; Bugg, Zook, DeLosh, Davalos, & Davis, 2006; Johnson & Deary, 2011), this raises the possibility that previous studies showing a link between goal neglect and gF are actually measuring processing speed.

## A combined analysis of three experiments

In the current study, we further explore the relationship between goal neglect, goal maintenance load, and both gF and processing speed. Initially, we present a series of three experiments which manipulated goal maintenance load through the number and complexity of instructions to be maintained by participants (i.e., instruction load). Each experiment presented participants with either 3 task instructions (low instruction load) or more task instructions (4 or 5 instructions; high instruction load). Although the three experiments manipulated instruction load in subtly different ways, they adopted very similar methodology and involved very similar groups of participants. As such, they are reported together to facilitate comparisons between the conditions and to improve statistical power.

The contribution of both gF and processing speed to goal neglect was assessed across the 3 experiments. If, as suggested by previous work (e.g., Duncan et al., 1996), higher gF is related to the ability to maintain more task rules, then associations between gF test scores and the rate of goal neglect should be particularly strong when the instruction load is high.

Instead, if processing speed is related to improved goal maintenance abilities, then controlling for individual differences in processing speed should attenuate any association between gF and goal neglect.

We examined the frequency of goal neglect separately in two age groups: younger and older adults. Several goal maintenance studies to date (e.g., Duncan et al., 2008) have recruited middle-aged or older adults in order to gain a wider distribution of gF scores, which is partly the result of age-related declines in gF (Horn & Cattell, 1967). However, declines in gF are accompanied by age-related slowing (e.g., Salthouse & Meinz, 1995; Salthouse, 1996), and statistically controlling for processing speeds has been shown to attenuate age-related differences on goal maintenance tasks (Fisk & Warr, 1996). Furthermore, the relationship between gF and processing speed is particularly strong in older adults (Bugg et al., 2006). It is therefore unclear whether individual differences in gF and processing speed are independent predictors of goal neglect in older adults, and whether younger adults might show similar associations despite their intact abilities. Age differences were not directly assessed, as more frequent goal neglect with increased instruction load should be observable in any individual who demonstrates lower levels of gF or processing speed, regardless of age (see Duncan et al., 2012).

## Methods

### Participants.

A power analysis based on the effect size of the interaction between instruction load and gF ($d = 0.8$) reported in Duncan et al. (2008) suggested that a minimum of 21 participants were required in each instruction load condition to achieve a power of 0.8.

In the first experiment, 48 older adults (aged 60-78 years) and 66 younger adults (aged 18-32 years) were recruited. In the second experiment, 44 older adults (aged 61-80 years) and 44 younger adults (aged 18-35 years) were recruited. In the third experiment, 41 younger adults (aged 18-34 years) were recruited; no older adults took part in this experiment. None of the participants took part in more than one of the experiments described, thus ensuring that the tasks and their rules were novel. Tables 1 and 2 provide the demographic information for younger and older adults in each condition.

- Insert Tables 1 and 2 around here -

**Procedure.**

***The letter-monitoring task (Duncan et al., 1996).*** The 3 experiments presented in the combined analysis manipulated instruction load in different ways, but used almost identical protocols and equipment. Each of the experiments used a letter-monitoring task – previously used by Duncan and colleagues (Duncan et al., 1996) – to measure goal neglect. This took the form of a rapid serial visual presentation task, administered on a Dell 15" laptop screen with participants seated approximately 50cm away. In each of 12 trials (8 trials in the second experiment), participants saw a series of white stimulus pairs (Arial font, 18pt) – either letter-pairs or number-pairs – presented one pair at a time in the center of a black background (an example trial is shown in Figure 1). All trials began with a first side instruction cue (FSI; "WATCH LEFT" or "WATCH RIGHT"), followed by 10 stimulus pairs, a second side instruction cue (SSI; "+" or "-"), and 3 further stimulus pairs. The FSI was presented for 1000ms and all other stimuli were presented for 200ms, with a 200ms inter-stimulus interval (ISI).

- Insert Figure 1 around here -

In all three experiments, participants were told a minimum of 3 instructions at the start of the task. The first instruction was to only report letters, and not numbers. The second instruction was to only report stimuli from the side of the screen indicated by the FSI cue. The third instruction was to attend to the side of the screen indicated by the SSI cue seen towards the end of the trial, with "+" indicating right and "-" indicating left. An example trial, along with the targets indicated by the FSI and SSI cues, is shown in Figure 1. It is use of the final SSI instruction which is affected by goal neglect (see Duncan et al., 1996; 2008). Beyond this baseline condition of 3-instructions, each of the three experiments manipulated instruction load in a subtly different way. In all three experiments, however, additional instructions were presented prior to the SSI-relevant instruction to preserve the temporal position of the rule (see Duncan et al., 1996).

The first experiment manipulated the number of instructions presented to participants. Younger and older adult groups performed either a 3- or a 4-instruction condition, and a group of younger adults performed a 5-instruction condition. In the 4-instruction condition, participants were additionally told to only report upper-case (i.e., capitalized) letters, and to ignore lower-case letters. In the 5-instruction condition, another instruction was added which was to ignore any character (even upper-case letters) on the attended side if it was presented in red. None of the characters were presented in lower-case or in red font, making all additional instructions irrelevant to the task at-hand.

In the second experiment, the additional instruction in the 4-instruction condition – to ignore lower-case letters – was required to be used during the task. This was achieved by replacing three number-pairs with lower-case letter-pairs.

In the third experiment, the rule regarding the SSI was changed so that a '–' required participants to switch sides and a '+' required them to stay on the same side (rather than the absolute directions used in Experiments 1 and 2). In the 4-instruction condition, participants were told that either letters or numbers could appear in red ink, and when they did, they should switch to reporting numbers (still on the same side) for the remainder of the trial. As in Experiment 1, this rule was never used as there were never any red characters in any of the trials.

Participants received at least 2 practice trials identical to the actual task trials, before being asked to repeat the task rules. Practice trials ended as soon as participants reported any letters and correctly recalled the SSI rule. In the second experiment, practice trials included lower-case letters. The majority of participants across all three experiments required only 2 practice trials before correctly recalling the task rules. Regardless of the instruction load condition, all participants were able to repeat the instructions upon prompting both after the practice and after the task itself.

Performance on each trial of the letter-monitoring task was divided into two phases; before and after the SSI cue. Duncan and colleagues (2008) demonstrated that goal neglect does not manifest in the pre-SSI phase of the task, and that performance in this phase is sensitive to the difficulty of the task, not manipulations of instruction load. Since goal neglect typically manifests as poor use of the SSI rule (e.g., failing to report letters from the right side following a '+' cue), only performance in the post-SSI phase should be sensitive to manipulations of instruction load. Therefore, performance is measured using two independent metrics: one based on performance in the pre-SSI phase and reflecting task difficulty, and one based on performance in the post-SSI phase and reflecting goal neglect. In line with Duncan et al. (2008), pre-SSI performance was measured by calculating the percentage of correct responses made from the cued side of the first 10 stimulus pairs and goal neglect was measured by calculating the Side Error score from the final 3 stimulus pairs. The Side Error score is a weighted ratio (from 0 to 1) where higher scores indicate more frequent intrusion errors. During the post-SSI phase, if more correct responses are given than intrusion errors then the trial receives a Side Error score of 0, but if more intrusion errors are made than correct responses then the trial receives a Side Error score of 1. A Side Error score of 0.5 is given if equal numbers of correct responses and intrusion errors are made, or if no responses are given during the post-SSI phase. As in Duncan et al. (2008), the Side Error scores were averaged across all 12 trials to produce a Mean Side Error (MSE) score, which was used as an indicator of the frequency of goal neglect during the task. Neglect of the SSI cue most commonly leads to participants reporting from the same side as cued by the FSI, thus a MSE score of 0.5 would indicate goal neglect on 6/12 trials.

***The Cattell Culture Fair Test of Intelligence (Institute for Personality and Ability Testing, 1973).*** Each participant performed the Cattell Culture Fair (CCF) Test of Intelligence Form 2A (Institute for Personality and Ability Testing, 1973). The CCF was chosen to coincide with previous work on goal maintenance and general fluid intelligence (gF; e.g., Duncan et al., 1996; 2008). Test manual reports the reliability of the CCF Form 2A as 0.76. A large portion of performance on the CCF Form 2A is attributable to gF, with a squared correlation of 0.66. Furthermore, performance on the CCF correlates well with other common measures of gF such as Raven's Progressive Matrices ($r = 0.68$; Engle, Tuholski, Laughlin, & Conway, 1999). Raw scores were converted to standardized full-scale intelligence scores (i.e., IQ scores; $M = 100$, $SD = 15$), which were used as a measure gF.

***Addenbrooke's Cognitive Examination – Revised (Mioshi, Dawson, Mitchell, Arnold, & Hodges, 2006).*** The Addenbrooke's Cognitive Examination-Revised (ACE-R) was administered as a brief assessment of overall cognition. The ACE-R is commonly used as a cognitive screening test which includes orientation and attention, memory, verbal fluency, language, and visuo-spatial abilities (see Mioshi et al., 2006). A cut-off score of 82 out of 100 is used to indicate cognitive impairment. The present study administered the ACE-R to both younger and older participants.

***The Inspection Time task.*** The Inspection Time (IT) task was administered as a background test to assess speed of processing. Participants were required to decide whether the two antennae of an alien were the same or different lengths, with an equal number of each trial type. Stimuli were presented in white on a black background. Trials began with a fixation cross presented for 200ms prior to the alien appearing. After the alien was presented for a particular exposure duration, it was covered by a backward mask, and responses ("same" or "different") were made using one of two shoulder buttons on a games controller. Trials were presented in two interleaved staircases of 65 trials (130 trials total, split across 5 blocks), with each stair beginning with an exposure duration of 267ms. The current exposure duration in the staircase was assigned according to a PEST procedure (Findlay, 1978; Pentland, 1980; Anderson, Bucks, Bayliss, & Della Sala, 2011), which adjusts the exposure duration of the next trial to achieve a 70% accuracy on a given stair. If accuracy on the stair so-far was below 70% then the exposure duration was increased, but if accuracy was above 70% then the exposure duration was decreased. Accuracy was encouraged over speed, and accuracy feedback was provided after each block. IT was estimated by averaging the exposure duration for the last 5 trials of each staircase, and then averaging these two means.

***The Reaction Time task.*** The Reaction Time (RT) task was based on the IT task described above, and was included as another background measure of processing speed. The task was the same as the IT task except the alien remained on the screen until the participant responded (i.e., there was no set maximum duration), and was not covered by a mask. Additionally, a screen presented before the last block instructed participants that the response mappings of the shoulder buttons were now reversed. Participants were encouraged to respond as quickly but as accurately as possible, and feedback at the end of each block indicated the accuracy and average response time (RT) in ms for that block. RT was defined as the mean correct reaction time, averaged across blocks, after removing responses more than 3 standard deviations above or below the mean and responses under 200ms. Across all 3 experiments, this cleaning removed a mean of 3.81% of trials per participant (*SD* = 1.41). The percentage of trials removed did not significantly differ between experiments ($p = 0.84$) or between younger and older adults ($p = 0.08$).

Where the IT task limits the time for which stimuli are presented, the RT task limits (through encouraging fast responses) the time available to make a response. Therefore, the IT task measures the speed at which participants can visually attend and encode stimuli, and the RT task measures the speed at which they can select and generate a response appropriate to the encoded stimuli.

**Data analysis.** As all three experiments manipulated instruction load, a categorical variable was created to represent high or low instruction load. The 3-instruction conditions contributed to the 'low' load category, and the 4- and 5-instruction conditions contributed to the 'high' load category.

Demographic variables and pre-SSI performance were analyzed using between-subjects ANOVAs including Experiment (1, 2 or 3), age group (younger or older), and instruction load (high-load or low-load). Regression was used for the analysis of goal neglect to allow the linear effects of gF and processing speed to be assessed alongside experimental manipulations. Multiple stepwise regression analyses were conducted to predict MSE scores in each age group. In step 1, a full-factor model was created including Experiment (1, 2, or 3), instruction load (high-load or low-load), age (in years), gF (IQ scores), and processing speed (estimated IT and estimated correct RT considered separately). Experiment was removed in step 2, instruction load in step 3, age in step 4, IQ scores in step 5, estimated IT in step 6, and estimated RT in step 7. The contribution and significance of each predictor was estimated at each step, as well as the change in fit of the overall model after removing the appropriate variable.

As well as calculating frequentist statistics (i.e., p-values), Bayes Factors were calculated for the models at each step of the regression analyses using the BayesFactor package for R (v 0.9.12-2; Morey, Rouder, & Jamil, 2015). Bayes Factors are used to compare the fit of models to the given data (in this case, which model fits MSE scores), and in contrast to frequentist approaches, provide some estimate of evidence in favour of a null hypotheses (Jeffreys, 1961). Such contrasts are achieved by dividing the Bayes Factor generated for the hypothesised model by the Bayes Factor generated for the competing (or null) model. As the resulting ratio increases beyond 1 and towards positive infinity, the evidence for the hypothesised model afforded by the data becomes stronger. Likewise, as the ratio decreases beyond 1 and towards 0, the evidence for the competing model afforded by the data becomes stronger.

Finally, Pearson's correlations (two-tailed) were calculated for each instruction load condition in order to assess the relationship between task performance (pre-SSI proportion correct and post-SSI MSE scores separately) and either IQ scores, estimated IT, or estimated RT. These correlations were subjected to nonparametric bootstrapping analyses (see Roberts & Anderson, 2014; Preacher & Hayes, 2004). 95% confidence intervals were calculated over 1000 iterations, using the bias-corrected and accelerated method to adjust for skewness in the distribution (see also DiCiccio & Efron, 1996). Analyses were conducted in R (v2.13.1) and IBM SPSS Statistics (v19).

## Results

### Demographic variables.

All participants scored above the lower cut-off score of 82 out of 100 on the ACE-R, except one younger participant who scored 81. Removing this participant did not change the pattern of results and therefore the participant remained in the analyses. An ANOVA conducted on ACE-R scores showed no significant main effects of experiment, $F(2, 192) = 2.39$, *Mean Squared Error* = 27.15, $p = 0.09$, $\eta_p^2 = 0.02$, age group, $F(1, 192) = 3.07$, *Mean Squared Error* = 34.91, $p = 0.08$, $\eta_p^2 = 0.02$, or instruction load condition, $F(1, 192) = 0.22$, *Mean Squared Error* = 2.46, $p = 0.64$, $\eta_p^2 < 0.01$. There was likewise no significant 2-way interactions (all *p*s > 0.12) or a significant 3-way interaction, $F(1, 192) = 3.60$, *Mean Squared Error* = 40.84, $p = 0.06$, $\eta_p^2 = 0.02$.

One participant did not disclose the number of years spent in full-time education. For all other participants, an ANOVA conducted on full-time education showed a significant main effect of experiment, $F(2, 232) = 6.34$, *Mean Squared Error* = 46.05, $p < 0.01$, $\eta_p^2 = 0.05$. This was driven by significantly fewer years of education in the first experiment (M = 15.85 years, SD = 2.68) than in the second experiment (M = 17.17 years, SD = 3.00), $t(176) = 3.24$, $p < 0.01$, $d = 0.49$, *95% CI* [-2.13, -0.52]. There was no significant main effects of age group, $F(1, 232) = 3.11$, *Mean Squared Error* = 22.57, $p = 0.08$, $\eta_p^2 = 0.01$, or instruction load condition, $F(1, 232) = 1.82$, *Mean Squared Error* = 13.20, $p = 0.18$, $\eta_p^2 = 0.01$. None of the 2-way or 3-way interactions were significant (all *p*s > 0.27).

Younger adults (M = 120.17, SD = 15.90) exhibited significantly higher IQ scores than older adults (M = 97.07, SD = 12.51), $F(1, 233) = 110.46$, *Mean Squared Error* = 24258.56, $p < 0.01$, $\eta_p^2 = 0.32$. There was no significant main effect of experiment, $F(2, 233) = 0.97$, *Mean Squared Error* = 212.09, $p = 0.38$, $\eta_p^2 = 0.01$, or instruction load condition, $F(1, 233) = 1.83$, *Mean Squared Error* = 402.73, $p = 0.18$, $\eta_p^2 = 0.01$. None of the 2-way or 3-way interaction effects were significant (all *p*s > 0.72).

The two processing speed measures were also examined using a 3-way ANOVA including experiment, age group, and instruction load condition. For ITs, there was no significant main effect of experiment, $F(2, 233) = 0.30$, *Mean Squared Error* = 76.08, $p = 0.74$, $\eta_p^2 < 0.01$, or instruction load condition, $F(1, 233) = 0.58$, *Mean Squared Error* = 145.04, $p = 0.45$, $\eta_p^2 < 0.01$. There was a significant main effect of age group, with older adults (M = 67.37ms, SD = 21.10) demonstrating slower ITs than younger adults (M = 38.84ms, SD = 11.35), $F(1, 233) = 156.15$, *Mean Squared Error* = 39018.94, $p < 0.01$, $\eta_p^2 = 0.40$. None of the 2-way or 3-way interactions were significant (all *p*s > 0.16). The same pattern of results was observed in terms of RTs. There were no significant main effects of experiment, $F(1, 233) = 0.33$, *Mean Squared Error* = 1603.88, $p = 0.72$, $\eta_p^2 < 0.01$, or instruction load condition, $F(1, 233) = 0.06$, *Mean Squared Error* = 314.66, $p = 0.80$, $\eta_p^2 < 0.01$. Older adults (M = 676.25ms, SD = 78.29) exhibited slower RTs than younger adults (M = 524.81ms, SD = 63.91), $F(1, 233) = 230.25$, *Mean Squared Error* = 1135092.27, $p < 0.01$, $\eta_p^2 = 0.50$. No 2-way or 3-way interaction was significant (all *p*s > 0.30).

**Pre-Second Side Instruction performance.**

A 3-way ANOVA was conducted on the percentage of correct responses made during the pre-SSI phase of the letter-monitoring task. There was no significant main effect of experiment, $F(2, 233) = 0.71$, *Mean Squared Error* < 0.01, $p = 0.49$, $\eta_p^2 = 0.01$, age group,

$F$(1, 233) = 0.24, *Mean Squared Error* < 0.01, $p = 0.62$, $\eta_p^2 < 0.01$, or instruction load condition, $F$(1, 233) = 1.76, *Mean Squared Error* < 0.01, $p = 0.19$, $\eta_p^2 = 0.01$. There was no significant 2-way interaction between age group and experiment, $F$(1, 233) = 0.17, *Mean Squared Error* < 0.01, $p = 0.68$, $\eta_p^2 < 0.01$, or between age group and instruction load, $F$(1, 233) = 2.54, *Mean Squared Error* < 0.01, $p = 0.11$, $\eta_p^2 = 0.01$. There was, however, a significant interaction between experiment and instruction load, $F$(2, 233) = 4.05, *Mean Squared Error* < 0.01, $p < 0.05$, $\eta_p^2 = 0.03$. This was driven by instruction load effects in Experiment 2, with poorer pre-SSI accuracy in the low instruction load condition (M = 0.97, SD = 0.03) than in the high instruction load condition (M = 0.99, SD = 0.02), $t$(70) = 2.87, $p < 0.01$, $d = 0.69$, *95% CI* [-0.03, -0.01]. Note that pre-SSI accuracy was still high (over 95%) in both instruction load conditions. Instruction load effects were not significant in the other experiments ($p$s > 0.45). The 3-way interaction between experiment, age group, and instruction load was not significant, $F$(1, 233) = 0.73, *Mean Squared Error* < 0.01, $p = 0.39$, $\eta_p^2 < 0.01$.

**Goal neglect.**

Due to the differences between the age groups both in terms of processing speed and gF, the younger and older adult age groups were examined separately.

- Insert Table 3 around here -

***Younger adults.*** The full model entered at step 1 significantly predicted MSE scores, $F$(7, 143) = 2.61, *Mean Squared Error* = 0.01, $p < 0.05$, with both experiment and IQ scores significantly contributing to the fit of the model. The contribution of experiment was driven by significantly lower MSE scores in Experiment 3 than either Experiment 1, $t$(101) = 3.22, $p$

< 0.01, $d = 0.64$, *95% CI* [0.02, 0.10], or Experiment 2, $t(59) = 2.88$, $p < 0.01$, $d = 0.75$, *95% CI* [0.02, 0.12] (see Table 1 for means and SDs). Higher IQ scores predicted lower MSE scores, and so less frequent goal neglect (see Table 3). Instruction load, estimated IT and estimated RT made no significant contribution to the model at any stage. Removal of experiment, *F change* (1, 143) = 4.36, $p < 0.05$, and gF, *F change* (1, 147) = 4.95, $p < 0.05$, significantly reduced the fit of the model. After the removal of experiment at step 2 the fit of the model become non-significant, $F(5, 145) = 1.83$, *Mean Squared Error* = 0.01, $p = 0.11$. In any case, the overall fit of the model was relatively poor, with only around 11% of the variance in MSE explained by the initial full-factor model. Furthermore, Bayesian analyses demonstrated poor support for any of the models, with only negligible support for the effects of experiment and IQ scores.

The correlation between IQ scores and MSE scores remained significant when IT and RT measures were partialled out, $r = -0.18$, $p < 0.05$, *BCa 95% CI* [-0.33, -0.02]. In contrast, the partial correlations between IT and MSE scores and between RT and MSE scores were not significant, when controlling for IQ scores: IT, $r = -0.04$, $p = 0.61$, *BCa 95% CI* [-0.20, 0.12]; RT, $r = 0.05$, $p = 0.56$, *BCa 95% CI* [-0.11, 0.21].

***Older adults.*** The full model including all six variables significantly predicted MSE scores, $F(6, 85) = 6.35$, *Mean Squared Error* = 0.03, $p < 0.001$. Age and RT were the only variables which made a significant contribution to the model for older adults. Both older age and slower RTs predicted higher MSE scores, and so more frequent goal neglect (Table 3). Removing age from the model at step 4 significantly reduced the fit, *F change* (1, 87) = 5.23, $p < 0.05$. Removing IT at step 6 also significantly reduced model fit, *F change* (1, 89) = 4.30, $p < 0.05$, as did removing RT at step 7, *F change* (1, 90) = 20.63, $p < 0.001$. Removing experiment, instruction load, or IQ scores made no significant change in the ability of the model to predict MSE scores. The model fit remained significant throughout the analysis (all $p < 0.001$), until estimated IT and estimated RT were removed in the final steps. The model of MSE performance of older individuals predicted 31% of the variance in the initial full-factor model (decreasing to 19% at step 6). Bayesian analyses (Table 3) showed minimal support for the effect of age and IT, and minimal support against the effect of IQ score (relative to a model with only IT and RT). Importantly, the data provided extremely strong support for the effect of RT on the rate of goal neglect.

A partial correlation conducted between IQ scores and MSE scores, when controlling for estimated IT and RT, was not significant, $r = -0.10$, $p = 0.34$, *BCa 95% CI* [-0.30, 0.11]. In contrast, significant positive correlations were observed between IT and MSE scores, $r = 0.24$, $p < 0.05$, *BCa 95% CI* [0.04, 0.43], and between RT and MSE scores, $r = 0.33$, $p < 0.01$, *BCa 95% CI* [0.13, 0.50] when controlling for IQ scores.



**Discussion**

The combined analysis presented above examined the effects of instruction load, gF, and processing speed on the rate of goal neglect during a complex letter-monitoring task. For younger adults, higher gF somewhat predicted lower rates of goal neglect on the letter-monitoring task, and this association remained after accounting for processing speed. In older adults, however, gF played no such role. Instead, processing speed (and age) predicted the rate of goal neglect, with slower speeds associated with more frequent neglect. Furthermore, in the older adult group, accounting for processing speed attenuated any association between goal neglect and gF.

Instruction load did not significantly predict the frequency of goal neglect for either age group. This is in direct contrast to previous work (e.g., Duncan et al., 2008; Roberts &

Anderson, 2014) which has reported increasing goal neglect with increasingly complex instructions. This difference may be due to the way in which instruction load was manipulated. Each of the three experiments in the present study manipulated the number of distinct rules presented during the instruction phase prior to a single task. In Duncan et al. (2008), however, the high instruction load condition required participants to maintain two sets of similar task instructions (regarding a letter task and a number task) over the course of a given task. In such a paradigm, goal maintenance load may derive from the need to maintain two somewhat-overlapping sets of task rules concurrently, rather than from the need to maintain more task rules *per se*. This is consistent with previous suggestions that goal maintenance reflects the ability to maintain task rules when other similar rules compete for working memory resources (Kane & Engle, 2003; Morey et al., 2012).

Instead of being limited by instruction load, the strong association between goal neglect and RTs in older adults suggests that the goal maintenance system may be limited in the speed at which it can bias or upregulate attention to the relevant goals. RT played a more important role in predicting goal neglect than IT. The IT task limited the initial presentation time of stimuli but did not limit the response window. In contrast, the RT task did not limit the initial presentation time, but did encourage the production of fast responses. The predictive value of RT rather than IT task performance in the letter-monitoring task may therefore relate to the need to use the SSI cue within a time-limited window, rather than the need to direct visual attention to the rapidly-presented SSI cue. Indeed, the dynamic re-biasing of attention to specific goals is a process which takes time to complete (Notebaert et al., 2006; Sharma et al., 2010). Processing speed may therefore determine how fast task-relevant rules can be activated sufficiently for use. Individuals with slow processing speeds may be unable to activate and use the SSI rule within the time demands of the letter-monitoring task, resulting in the inappropriate and repeated use of the FSI-relevant rule. In 'stay' trials, this perseverative use of task rules may be without cost as both FSI and SSI cues indicate the same stimuli. However, in 'switch' trials, such behavior leads to the kind of inappropriate FSI-guided responses (and so high MSE scores) previously reported in the literature (e.g., Duncan et al., 1996).

To confirm the speed limitation of goal maintenance, a further experiment was conducted which reduced the inter-stimulus interval (ISI) of the letter-monitoring task from 200ms (used in the experiments described above) to 160ms, thus limiting the time available for activating and using task rules before the next targets appear. This faster task condition should increase the rate of goal neglect (and so MSE scores), particularly in those individuals with slower processing speeds. Given the subtlety of the speed increase, individuals with faster processing speeds should be relatively unaffected by the change in ISI. As before, the relative contributions of gF and processing speed were assessed in across the letter-monitoring task conditions.



## Experiment 4

### Methods

#### Participants.

Twenty-two younger adults aged 18-35 years (M = 21.81, SD = 4.64) and 24 older adults aged 60-84 years (M = 72.90, SD = 6.80) took part in this experiment. None of them had taken part in any of the previously reported experiments. All participants were administered the 160ms ISI version of the letter-monitoring task and this was contrasted with the performance of the participants in the 3-instruction (200ms ISI) condition in Experiment 1. One younger participant and two older participants in the 160ms ISI condition were removed from the analyses as they were outliers with IT estimates that were around 4 SDs from their respective age group means (93.33ms, 361.11ms, and 271.11ms respectively). The analyses were therefore based on the data of 43 younger adults and 46 older adults when combined with the 200ms ISI condition data taken from Experiment 1 (22 younger adults and 24 older adults). The demographic data for younger and older participants are summarized in Table 4.

- Insert Table 4 around here -

**Procedure.**

***The letter-monitoring task.*** The same 3-instruction letter-monitoring task as in Experiment 2 was administered except the inter-stimulus interval (ISI) was reduced to 160ms. Pilot testing showed that any ISI faster than 160ms produced floor effects, both pre- and post-SSI. Pre-SSI performance and MSE scores were calculated as in previous experiments.

The same background tests were administered as in Experiments 1, 2, and 3: CCF Form 2A to measure gF (IQ scores), the ACE-R to assess general cognitive function, and the IT task and RT task to measure processing speed. In the RT task, the cleaning process removed a mean of 3.74% of trials per participant ($SD$ = 1.53). The percentage of removed trials did not significantly differ between younger and older adults ($p$ = 0.87).

**Data analysis.**

Letter-monitoring task performance was compared with the data from the 3-instruction condition in Experiment 1, which was identical except the ISI was 200ms rather than 160ms.

Two additive stepwise regression analyses were conducted in order to assess the separate contributions of gF and processing speed in the neglect of the SSI rule. A baseline model was constructed to predict MSE scores using only ISI condition as a predictor. In the first regression analysis, the main effect of IQ score was added to the baseline model, and the two models contrasted. An interaction term between IQ score and ISI condition was then added, and the resulting model compared to the main effects-only model. In the second regression analysis, this process was repeated but with IQ score replaced by IT and RT estimates (no interaction term was included between ITs and RTs). The gF and processing speed models were then compared for both the main effects-only and interaction models. Bayes factors were calculated and contrasted between each of the models to compare the evidence afforded by the data.



## Results

### Demographic variables.

On the ACE-R, all participants scored above the lower cut-off score of 82 out of 100 (Younger: M = 94.08, SD = 4.17; Older: M = 96.39, SD = 2.96). For younger adults, there was no significant difference between participants in the 160ms and 200ms ISI conditions in terms of age, $t(41) = 0.10$, $p = 0.92$, $d = 0.03$, *95% CI* [-2.42, 2.68], time spent in full-time education, $t(41) = -0.28$, $p = 0.78$, $d = 0.09$, *95% CI* [-1.98, 1.50], IQ scores, $t(41) = -0.88$, $p = 0.38$, $d = 0.27$, *95% CI* [-13.96, 5.48], estimated IT, $t(41) = -0.27$, $p = 0.79$, $d = 0.08$, *95% CI* [-6.12, 4.68], or estimated RT, $t(41) = 0.89$, $p = 0.38$, $d = 0.28$, *95% CI* [-20.41, 52.42]. For older adults, those in the 160ms ISI condition were significantly older than those in the 200ms ISI condition, $t(44) = 3.18$, $p < 0.001$, $d = 0.96$, *95% CI* [2.09, 9.40]. However, there was no such difference between older participants in the 160ms and 200ms ISI conditions in terms of the time spent in full-time education, $t(44) = 1.49$, $p = 0.14$, $d = 0.45$, *95% CI* [-0.48, 3.15], IQ scores, $t(44) = -0.06$, $p = 0.96$, $d = 0.02$, *95% CI* [-8.97, 8.49], estimated IT, $t(44) = -0.07$, $p = 0.94$, $d = 0.02$, *95% CI* [-9.70, 9.03], or estimated RT, $t(44) = 0.56$, $p = 0.58$, $d = 0.17$, *95% CI* [-36.41, 64.50].

**Pre-Second Side Instruction performance.**

Table 4 demonstrates the means and standard deviations for the younger and older adults performing the 160ms and 200ms ISI conditions. Younger adults in the 160ms condition correctly reported significantly fewer pre-SSI letters than those in the 200ms ISI condition, $t(41) = 3.28$, $p < 0.01$, $d = 1.02$, *95% CI* [0.01, 0.04]. Older adults showed no significant effect of ISI condition in their pre-SSI performance, $t(44) = 1.99$, $p = 0.06$, $d = 0.60$, *95% CI* [-0.0004, 0.04].

**Goal Neglect.**

***Younger adults.*** The initial model including only ISI condition did not significantly predict MSE scores, $F(1, 41) = 0.66$, *Mean Squared Error* = 0.02, $p = 0.42$, and only accounted for 2% of the variation in MSE scores.

Adding a main effect of IQ score significantly improved model fit, *F change* (1, 40) = 7.68, $p < 0.01$, and comparison of Bayes factors demonstrated substantial support for the updated model, $BF = 6.22$. The model significantly predicted around 13% of the variability in MSE scores, $F(2, 40) = 4.22$, *Mean Squared Error* = 0.02, $p < 0.05$. Only IQ score significantly contributed to the model, with higher IQ scores predicting lower MSE scores, $\beta < -0.01$, $p < 0.01$. Including an interaction effect between ISI condition and IQ score did not further improve model fit, *F change* (1, 40) = 1.42, $p = 0.24$, and comparison of Bayes factors showed minimal support against the updated model, $BF = 0.60$. The model predicted around

14% of the variability in MSE scores, $F(3, 39) = 3.32$, *Mean Squared Error* = 0.02, $p < 0.03$. The interaction effect did not significantly predict MSE scores, $\beta > -0.01$, $p = 0.24$.

When the main effects of IT and RT were simultaneously added to the model including ISI condition, there was no significant change in model fit, *F change* (2, 39) = 0.66, $p = 0.52$, and comparison of Bayes factors showed substantial evidence against the updated model, $BF = 0.21$. The model did not significantly predict MSE scores, $F(3, 39) = 0.66$, *Mean Squared Error* = 0.02, $p = 0.58$. Neither the main effect of IT, $\beta < 0.01$, $p = 0.38$, or RT, $\beta < 0.01$, $p = 0.48$, significantly contributed to the model. Including interaction effects between ISI condition and both IT and RT estimates did not significantly improve model fit, *F change* (2, 37) = 0.43, $p = 0.66$, and comparison of Bayes factors showed minimal evidence against the updated model, $BF = 0.35$. The model including the interaction term did not significantly predict MSE scores, $F(5, 37) = 0.55$, *Mean Squared Error* = 0.02, $p = 0.73$. Neither the interaction effect between ISI condition and IT, $\beta < 0.01$, $p = 0.49$, or between ISI condition and RT, $\beta < 0.01$, $p = 0.57$, significantly contributed to the model.

Comparing the Bayes factors of the two main effects-only models (IQ scores vs IT and RT estimates) showed strong evidence in favor of the model including ISI condition and IQ score, $BF = 29.67$. Likewise, there was very strong evidence in favor of the model including an interaction term between ISI condition and IQ score, relative to the model including an interaction term between ISI condition and both IT and RT estimates, $BF = 50.56$. A full model including ISI condition as well as main and interaction effects of IQ score, IT and RT did not significantly predict MSE scores, $F(7, 35) = 1.46$, *Mean Squared Error* = 0.02, $p = 0.21$. None of the predictors significantly contributed to the model (all *p*s > 0.23).

***Older adults.*** For older adults, the initial model including only ISI condition significantly predicted the rate of goal neglect exhibited on the task, $F(1, 44) = 5.80$, *Mean Squared Error* = 0.05, $p < 0.05$, and accounted for 10% of the variation in MSE scores. MSE scores were significantly higher in the 160ms ISI condition than in the 200ms ISI condition, $t(44) = 2.43$, $p < 0.05$, $d = 0.73$, *95% CI* [-0.28, -0.03] (see Table 4), indicating more frequent neglect of the SSI rule in the faster condition.

Adding a main effect of IQ score significantly improved model fit, *F change* (1, 43) = 13.28, $p < 0.001$, and comparison of Bayes factors with the ISI condition-only model showed very strong evidence in favour of the model additionally including IQ score, $BF = 41.09$. The model significantly predicted around 29% of the variation in MSE scores, $F(2, 43) = 10.35$, *Mean Squared Error* = 0.03, $p < 0.001$. In this model, both ISI condition, $\beta = 0.15$, $p < 0.05$, and the main effect of IQ score, $\beta = -0.01$, $p < 0.001$, significantly contributed to the model. Further adding the interaction effect between ISI condition and IQ score did not improve model fit, *F change* (1, 42) = 0.93, $p = 0.34$, and comparison of Bayes factors demonstrated minimal evidence in favour of the main effect-only model, $BF = 0.44$. The model including the interaction effect significantly predicted 29% of the variance in MSE scores, $F(2, 42) = 7.20$, *Mean Squared Error* = 0.03, $p < 0.001$. However, none of the predictors significantly contributed to model fit (all *p*s > 0.07).

When the main effects of IT and RT were simultaneously added to the model including ISI condition there was a significant improvement in model fit, *F change* (2, 42) = 11.50, $p < 0.001$, and comparison of Bayes factors showed decisive evidence in favour of the updated model, $BF = 286.68$. The model significantly predicted around 39% of the variance in MSE scores, $F(3, 42) = 10.53$, *Mean Squared Error* = 0.03, $p < 0.001$. In this model, MSE scores were significantly predicted by ISI condition, $\beta = 0.14$, $p < 0.05$, and by RTs, $\beta < 0.01$, $p < 0.001$, with slower RTs predicting more frequent goal neglect. Adding interaction effects between ISI condition and both IT and RT estimates did not improve model fit, *F change* (2, 40) = 1.41, $p = 0.26$, and comparison of Bayes factors showed minimal evidence in favour of the main effects-only model, $BF = 0.34$. The model significantly predicted 40% of the variance in MSE scores, $F(5, 40) = 7.01$, *Mean Squared Error* = 0.03, $p < 0.001$. Only the main effect of RTs significantly contributed to the model, $\beta < 0.01$, $p < 0.01$, with slower RTs predicting more frequent goal neglect (all other *p*s > 0.11).

Comparing Bayes factors of the two main effects-only models (IQ scores vs. IT and RT estimates) showed substantial evidence in favour of the model including IT, RT and ISI condition, $BF = 6.98$. Likewise, there was substantial evidence in favour of the interaction model including IT and RT relative to the interaction model including IQ score, $BF = 5.43$. A full model including ISI condition, IQ score, estimated IT, estimated RT, and the respective interactions with ISI condition significantly predicted MSE scores, $F(7, 38) = 5.63$, *Mean Squared Error* = , $p < 0.001$. In this full model, only the main effect of RT contributed to model fit, $\beta < 0.01$, $p < 0.01$ (all other *p*s > 0.12).



**Discussion**

Experiment 4 examined whether the goal maintenance system is limited by the speed at which it can operate. By subtly increasing the speed at which the letter-monitoring task stimuli were presented, a stricter time limit was placed on the activation and use of the SSI-relevant rule (i.e., switch sides or stay on the same side). In line with this speed limitation, goal neglect was much more frequent in the faster (160ms) task condition, and the frequency of goal neglect was predicted by individual differences in processing speed, though only for older adults. This difference was despite the task rules themselves being identical for the 160ms and 200ms ISI tasks. These findings are analogous to presentation-rate effects demonstrated in the Stroop task (Notebaert et al., 2006; Sharma et al., 2010) where fast conditions (e.g., 50ms) result in frequent intrusion errors, particularly in older adults (De Jong, Berendsen, & Cools, 1999).

Although both ISI condition and RTs predicted the frequency of goal neglect in older adults, there was no significant interaction between the two. We had predicted that increasing the presentation rate of the task would be particularly problematic for those individuals with slower processing speed, as the activation of task goals may not be sufficiently modulated within these faster time constraints. The lack of interaction effect may suggest that the 200ms ISI condition is already fast enough so as to limit the goal maintenance system of older adults; activating the SSI-relevant rule may take longer than 200ms for some older adults. This may likewise explain the importance of processing speed in the combined analysis presented earlier, as it may index the speed with which a task rule can be activated.

## General Discussion

### A speed-limited goal maintenance system.

Unlike previous work (e.g., Duncan et al., 2008; Roberts & Anderson, 2014), no evidence for an instruction load effect on the rate of goal neglect was observed across 4 subtly different experiments. However, in contrast to previous work, the tasks and manipulations used here ensured that manipulating the number of task rules was not confounded with competition between task rules. The data suggest that the goal maintenance system is not capacity-limited, but is instead limited by the need to control and rebias attention across multiple task rules. Indeed, Experiment 4 demonstrated that this rebiasing takes time, and that reducing the amount of time available during a task makes goal neglect much more common, at least in older adults. This interpretation is consistent with previous work using the Stroop task. In the Stroop task, if the color-naming goal is not sufficiently maintained then the competing word-reading goal can control behavior, and this competition can be heightened by infrequently presenting incongruent trials (Kane & Engle, 2003; Morey et al., 2012). However, the activation of color-naming and word-reading goals can be modulated, and so competition dealt with, when there is sufficient time between trials (Notebaert et al., 2006; Sharma et al., 2010).

The suggestion of a speed-limited goal maintenance system is also supported by the involvement of individual differences in processing speed observed throughout the present study. Both the combined analysis of Experiments 1-3 and Experiment 4 showed that slower RTs predicted more frequent neglect of the SSI-relevant rule in older adults specifically. Given that, in older adults, goal neglect appears to be affected by reducing the window for goal activation, estimates of processing speed may represent some index of how fast sufficient activation can be achieved. Again, this is consistent with suggestions that the goal-driven modulation of competition within the Stroop task takes time (Notebaert et al., 2006; Sharma et al., 2010). Notably, the involvement of processing speed in the present task does not appear to be related to the difficulty of the task itself, or to limitations in visual attention. Indeed, the rate of goal neglect was not predicted by individual differences in IT, and all participants reported seeing the critical stimuli. This indicates that neglect-like behavior did not simply arise from inattention to the briefly-presented SSI cue, a finding which is consistent with previous goal maintenance work (Duncan et al., 1996; Iveson, Tanida, & Saito, 2016).

**The role of fluid intelligence.**

In both the combined analysis of Experiments 1-3 and Experiment 4, individual differences in gF predicted a significant proportion of the variance in the rate of goal neglect exhibited by individuals. However, in younger adults, the amount of variance in goal neglect predicted by IQ scores was much smaller than for older adults. In older adults, IQ scores predicted MSE scores only until RTs were accounted for. That is, the association between the frequency of goal neglect and gF was attenuated by processing speed. Importantly, the association between goal neglect and processing speed was not attenuated by gF, and Bayesian analyses favored processing speed models when compared to gF models. This was not the case for younger adults, for whom the gF-goal neglect association was not attenuated by processing speed in Experiments 1-3 and for whom Bayesian analyses favored gF models over processing speed models in Experiment 4. This suggests that many of the associations drawn between goal neglect and gF in previous work (e.g., Duncan et al., 1996; Duncan et al., 2008; Roberts & Anderson, 2014) persist only in younger adults, and instead may be subsumed by individual differences in processing speed in older adults. Indeed, processing speed and gF are very strongly correlated (e.g., Jensen, 2006; Johnson & Deary, 2011), particularly in older adults (Bugg et al., 2006), and age-related changes in processing speed are thought to underlie much of the declines in gF observed in older adults (Salthouse, Fristoe, McGuthry, & Hambrick, 1998). Many researchers have posited processing speed as a fundamental component of gF abilities (e.g., Vernon, 1983; Bates & Stough, 1998). Further work is needed to elucidate the structure of the associations between processing speed and gF in relation to goal neglect, both in the letter-monitoring task and in other goal maintenance tasks.

**Age-related differences.**

Neither younger nor older adults were affected by manipulations which increased the number of instructions to be maintained. Furthermore, while older adults exhibited evidence for a speed-limited goal maintenance system, younger adults did not. In younger adults, processing speed measures did not predict MSE scores across any of the letter-monitoring tasks. Likewise, in Experiment 4, there was no effect of ISI condition for younger adults. Indeed, low MSE scores, indicating generally very good use of the SSI-relevant rule, were observed regardless of the ISI condition. This age-related difference in the rate of goal neglect and the effect of the ISI manipulation may simply be driven by large differences in processing speed between younger and older adults[1]. Indeed, a slowing of RTs is a prevalent feature of cognitive ageing (Salthouse, 1996). The faster processing speed of younger adults may facilitate quicker activation and use of the SSI rule, such that neither the 160ms ISI condition nor the 200ms ISI condition were sufficiently fast to tax goal maintenance.

The age-related difference in the importance of speed limitations may also reflect a more general tendency for older adults to adopt different strategies when faced with demanding tasks. Braver and colleagues (e.g., Braver, 2012; Braver & Barch, 2002; Braver et al., 2001; Paxton, Barch, Racine, & Braver, 2008) have suggested that older adults may adopt a reactive approach to goal maintenance due to declining working memory abilities, whereby task-relevant goals are only activated in response to external cues or prompts – such as the SSI prompt. This likely results in a strategy more sensitive to changes in presentation rate and more reliant on processing speed, as goal activation and use needs to be completed before the target stimuli appear. In the experiments presented above, older adults using a reactive strategy may not have been able to activate the SSI-relevant rule within the 160ms ISI before the following letter pairs, resulting in frequent goal neglect. Similarly, use of a reactive strategy may explain the importance of processing speed for older adults across the 200ms ISI versions of the letter-monitoring task. However, this is an admittedly post-hoc interpretation of the results, and the lack of a working memory measure in the present study makes it impossible to confirm that these declines are responsible for ISI effects in older adults. Further work should investigate whether individual differences in working memory ability can predict older adults' use of reactive strategies in the letter-monitoring task.

It is unclear whether younger adults are likewise adopting such a reactive approach but are simply unchallenged due to their faster processing speed, or whether younger adults adopt a different strategy altogether. Paxton et al. (2008) have suggested that younger adults may prefer a proactive approach to goal maintenance, whereby task-relevant goals such as the SSI rule are activated in advance of being required, allowing preparation for the upcoming response. Such a strategy would be insensitive to ISI manipulations and processing speed declines as task rules are already active when required. Instead, the key to determining the frequency of goal neglect in such a strategy may be the duration for which rules must be maintained (De Jong et al., 1999) and the competition between rules being maintained (Kane & Engle, 2003). The involvement of gF, albeit weakly, in the rate of goal neglect exhibited by younger adults may be some index of the intactness of the cognitive abilities upon which proactive strategies rely. Further work is required to dissociate these two approaches more directly, and to assess their associations with individual differences across the lifespan.

In summary, goal maintenance does not appear to be limited by the number of rules to be concurrently maintained. Instruction load effects in previous studies may result from competition between overlapping rules, rather than a taxing of goal maintenance capacity. Likewise, there appears to be little association between gF and the rate of goal neglect, at least in older adults. Instead, the present study demonstrates that goal maintenance is time-limited, in that reducing the time available for goal activation and use increases the rate of goal neglect. Similarly, individual differences in processing speed appear to be important for determining how fast individuals can rebias their attention within a set of task rules. Age-related differences in goal maintenance ability may result from age-related slowing of processing speed, or from a more fundamental shift away from a memory-demanding strategy and towards one more sensitive to the time demands of the task and the processing speed of the individual.

## References


Anderson, M., Bucks, R. S., Bayliss, D. M., & Della Sala, S. (2011). Effect of age on dual-task performance in children and adults. *Memory & Cognition, 39,* 1241–1252.

Bates, T., & Stough, C. (1998). Improved reaction time method, information processing speed, and intelligence. *Intelligence, 26*(1), 53–62.

Bhandari, A., & Duncan, J. (2014). Goal neglect and knowledge chunking in the construction of novel behaviour. *Cognition*, *130*(1), 11–30.

Braver, T. S. (2012). The variable nature of cognitive control: a dual mechanisms framework. *Trends in Cognitive Sciences*, *16*(2), 106–113.

Braver, T. S., & Barch, D. M. (2002). A theory of cognitive control, aging cognition, and neuromodulation. *Neuroscience and Biobehavioral Reviews*, *26*(7), 809–817.

Braver, T. S., Barch, D. M., Keys, B. A., Carter, C. S., Cohen, J. D., Kaye, J. A., … Reed, B. R. (2001). Context processing in older adults: Evidence for a theory relating cognitive control to neurobiology in healthy aging. *Journal of Experimental Psychology: General*, *130*(4), 746–763.

Bugg, J. M., Zook, N. A., DeLosh, E. L., Davalos, D. B., & Davis, H. P. (2006). Age differences in fluid intelligence: Contributions of general slowing and frontal decline. *Brain and Cognition, 62*, 9–16.

De Jong, R., Berendsen, E., & Cools, R. (1999). Goal neglect and inhibitory limitations: dissociable causes of interference effects in conflict situations. *Acta Psychologica*, *101*(2-3), 379–394.

DiCiccio, T., & Efron, B. (1996). Bootstrap confidence intervals. *Statistical Science*, *11*(3), 189–212.

Duncan, J., Burgess, P., & Emslie, H. (1995). Fluid intelligence after frontal lobe lesions. *Neuropsychologia*, *33*(3), 261–268.

Duncan, J., Emslie, H., Williams, P., Johnson, R., & Freer, C. (1996). Intelligence and the frontal lobe: the organization of goal-directed behavior. *Cognitive Psychology*, *30*(3), 257–303.

Duncan, J., Parr, A., Woolgar, A., Thompson, R., Bright, P., Cox, S., … Nimmo-Smith, I. (2008). Goal neglect and Spearman's g: competing parts of a complex task. *Journal of Experimental Psychology: General*, *137*(1), 131–148.

Duncan, J., Schramm, M., Thompson, R., & Dumontheil, I. (2012). Task rules, working memory, and fluid intelligence. *Psychonomic Bulletin & Review*, *19*(5), 864–870.

Engle, R. W., Tuholski, S. W., Laughlin, J. E., & Conway, A. R. (1999). Working memory, short-term memory, and general fluid intelligence: A latent-variable approach. *Journal of Experimental Psychology: General, 128*(3), 309–331.

Findlay, J. M. (1978). Estimates on probability functions: A more virulent PEST. *Perception and Psychophysics, 23(2),* 181–185.

Fisk, J. E., & Warr, P. (1996). Age and working memory: the role of perceptual speed, the central executive, and the phonological loop. *Psychology and Aging*, *11*(2), 316–323.

Horn, J. L., Cattell, R. B. (1967). Age differences in fluid and crystallized intelligence. *Acta Psychologica, 26*, 107-129.

Institute for Personality and Ability Testing. (1973). *Measuring intelligence with the Culture Fair tests.* Champaign, IL: The Institute for Personality and Ability Testing.

Jeffreys, H. (1961). *Theory of Probability* (3rd ed.). Oxford, U.K.: Oxford University Press.

Jensen, A. R. (2006). *Clocking the mind*. New York, NY: Elsevier.

Johnson, W., & Deary, I. J. (2011). Placing inspection time, reaction time, and perceptual speed in the broader context of cognitive ability: The VPR model in the Lothian Birth Cohort 1936. *Intelligence*, *39*(5), 405–417.

Kane, M. J., & Engle, R. W. (2003). Working-memory capacity and the control of attention: The contributions of goal neglect, response competition, and task set to Stroop interference. *Journal of Experimental Psychology: General*, *132*(1), 47–70.

Mioshi, E., Dawson, K., Mitchell, J., Arnold, R., & Hodges, J. R. (2006). The Addenbrooke's Cognitive Examination Revised (ACE-R): A brief cognitive test battery for dementia screening. *International Journal of Geriatric Psychiatry*, *21*, 1078–1085.

Morey, C. C., Elliott, E. M., Wiggers, J., Eaves, S. D., Shelton, J. T., & Mall, J. T. (2012). Goal-neglect links Stroop interference with working memory capacity. *Acta Psychologica, 141*, 250–260.

Morey, R. D., Rouder, J. N., Jamil, T. (2015). Package 'BayesFactor': Computation of Bayes Factors for Common Designs.

Notebaert, W., Gevers, W., Verbruggen, F., & Liefooghe, B. (2006). Top-down and bottom-up sequential modulations of congruency effects. *Psychonomic Bulletin & Review*, *13*(1), 112–117.

Paxton, J. L., Barch, D. M., Racine, C. A., & Braver, T. S. (2008). Cognitive control, goal maintenance, and prefrontal function in healthy aging. *Cerebral Cortex*, *18*(5), 1010–1028.

Pentland, A. (1980). Maximum likelihood estimation: The best PEST. *Perception and Psychophysics, 28(4),* 377–379.

Preacher, K. J., & Hayes, A. F. (2004). SPSS and SAS procedures for estimating indirect effects in simple mediation models. *Behavior Research Methods, Instruments, & Computers*, *36*(4), 717–731.

Roberts, G., & Anderson, M. (2014). Task structure complexity and goal neglect in typically developing children. *Journal of Experimental Child Psychology*, *120*, 59–72.

Roberts, G., Jones, T. W., Davis, E. A., Ly, T. T., & Anderson, M. (2014). Building tasks from verbal instructions: An EEG study on practice trial exposure and task structure complexity during novel sequences of behavior. *Cognitive, Affective, & Behavioral Neuroscience, 14*(4), 1356-1374.

Salthouse, T. A. (1996). The processing-speed theory of adult age differences in cognition. *Psychological Review*, *103*(3), 403–28.

Salthouse, T. A. (2005). Relations between cognitive abilities and measures of executive functioning. *Neuropsychology, 19*(4), 532–545.

Salthouse, T. A., Fristoe, N., McGuthry, K. E., & Hambrick, D. Z. (1998). Relation of task switching to speed, age, and fluid intelligence. *Psychology and Aging, 13*(3), 445–461.

Salthouse, T. A., & Meinz, E. J. (1995). Aging, inhibition, working memory, and speed. *Journal of Gerontology, 50*, 297–306.

Sharma, D., Booth, R., Brown, R., & Huguet, P. (2010). Exploring the temporal dynamics of social facilitation in the Stroop task. *Psychonomic Bulletin & Review*, *17*(1), 52–58.

Vernon, P. A. (1983). Speed of information processing and general intelligence. *Intelligence, 7*(1), 53–70.

Table 1

*Means and standard deviations (SD) for the younger participants performing in Experiments 1, 2 and 3.*

| | Experiment 1 | | | | | | Experiment 2 | | | | Experiment 3 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 3 Instructions | | 4 Instructions | | 5 Instructions | | 3 Instructions | | 4 Instructions | | 3 Instructions | | 4 Instructions | |
| | M | SD | M | SD | M | SD | M | SD | M | SD | M | SD | M | SD |
| Age (years) | 21.68 | 3.50 | 22.27 | 3.40 | 21.41 | 3.29 | 23.50 | 3.99 | 23.68 | 4.08 | 22.62 | 4.18 | 22.05 | 3.14 |
| Gender (Male/Female) | 9/13 | | 8/14 | | 4/18 | | 5/17 | | 10/12 | | 7/14 | | 4/16 | |
| Full-time education (years) | 16.00 | 2.60 | 16.57 | 2.03 | 16.18 | 1.92 | 17.64 | 2.98 | 17.05 | 2.65 | 16.81 | 1.99 | 16.30 | 2.00 |
| Handedness (L/A/R) | 4/1/17 | | 2/1/19 | | 1/0/21 | | 4/0/18 | | 4/0/18 | | 1/0/20 | | 6/1/13 | |
| ACE-R (max = 100) | 93.80 | 4.89 | 96.10 | 3.75 | 96.36 | 3.43 | 96.41 | 2.97 | 94.64 | 5.61 | 96.24 | 2.21 | 97.35 | 1.53 |
| Fluid Intelligence (IQ) | 120.95 | 16.25 | 120.32 | 14.46 | 118.95 | 15.69 | 119.23 | 18.10 | 116.82 | 16.74 | 125.24 | 18.12 | 119.85 | 11.75 |
| Inspection time (ms) | 37.17 | 9.14 | 41.06 | 15.02 | 39.85 | 11.41 | 43.74 | 11.81 | 34.49 | 10.15 | 36.24 | 10.00 | 39.28 | 9.50 |
| Correct reaction time (ms) | 523.09 | 65.38 | 510.59 | 56.51 | 524.09 | 65.21 | 540.73 | 72.70 | 515.18 | 70.93 | 517.57 | 45.39 | 543.80 | 68.13 |
| Pre-SSI proportion correct | 0.99 | 0.01 | 0.98 | 0.02 | 0.99 | 0.02 | 0.98 | 0.03 | 0.99 | 0.02 | 0.98 | 0.03 | 0.98 | 0.03 |
| MSE score | 0.05 | 0.08 | 0.05 | 0.08 | 0.04 | 0.05 | 0.11 | 0.14 | 0.05 | 0.08 | 0.03 | 0.04 | 0.01 | 0.03 |

L = left, A = ambidextrous, R = right; ACE-R = Addenbrooke's Cognitive Examination-Revised; SSI = Second Side Error; MSE = Mean Side Error

Table 2

*Means and standard deviations (SD) for the older participants performing in Experiments 1 and 2.*

| | Experiment 1 | | | | Experiment 2 | | | |
|---|---|---|---|---|---|---|---|---|
| | 3 Instructions | | 4 Instructions | | 3 Instructions | | 4 Instructions | |
| | M | SD | M | SD | M | SD | M | SD |
| Age (years) | 67.67 | 4.90 | 69.38 | 4.49 | 68.50 | 5.86 | 69.41 | 6.32 |
| Gender (Male/Female) | 9/15 | | 8/16 | | 4/18 | | 8/14 | |
| Full-time education (years) | 15.52 | 3.06 | 15.04 | 3.39 | 17.73 | 2.69 | 16.27 | 3.57 |
| Handedness (L/A/R) | 2/1/21 | | 3/0/21 | | 0/1/21 | | 1/0/21 | |
| ACE-R (max = 100) | 97.06 | 2.62 | 97.07 | 2.43 | 95.91 | 2.72 | 95.91 | 3.52 |
| Fluid Intelligence (IQ) | 98.88 | 13.89 | 96.04 | 12.75 | 97.50 | 13.57 | 95.77 | 9.87 |
| Inspection time (ms) | 70.05 | 26.44 | 66.85 | 16.08 | 67.63 | 21.12 | 64.75 | 20.46 |
| Correct reaction time (ms) | 681.00 | 76.54 | 668.50 | 78.81 | 672.86 | 76.61 | 682.91 | 85.54 |
| Pre-SSI proportion correct | 0.98 | 0.02 | 0.98 | 0.02 | 0.97 | 0.03 | 0.99 | 0.01 |
| MSE score | 0.18 | 0.19 | 0.18 | 0.19 | 0.17 | 0.16 | 0.26 | 0.23 |

L = left, A = ambidextrous, R = right; ACE-R = Addenbrooke's Cognitive Examination-Revised; SSI = Second Side Error; MSE = Mean Side Error

Table 3

*Multiple regression analysis for younger and older participants with the predictors removed in a stepwise fashion.*

| | | Younger | | | Older | | |
|---|---|---|---|---|---|---|---|
| Step | Measure removed | β | $\Delta R^2$ | BF | β | $\Delta R^2$ | BF |
| 2 | Experiment | -0.06** | -0.05* | 1.77 | -0.07 | -0.03 | 0.92 |
| 3 | Instruction Load | -0.03 | -0.02 | 0.74 | 0.04 | -0.01 | 0.33 |
| 4 | Age | <0.01 | <-0.01 | 0.36 | 0.01* | -0.04* | 2.89 |
| 5 | Fluid Intelligence | <0.01* | -0.03* | 2.69 | >-0.01 | >-0.01 | 0.40 |
| 6 | Inspection Time | >-0.01 | >-0.01 | 0.27 | <0.01 | -0.02* | 1.52 |
| 7 | Reaction Time | <0.01 | >-0.01 | 0.38 | <0.01* | -0.05*** | 1059.32 |

Note Shown are the standardized beta coefficients of each predictor in the full model, and the change in $R^2$ ($\Delta R^2$) and Bayes factor (BF) resulting from stepwise removal of the predictor based on the order listed. * $p < 0.05$, ** $p < 0.01$, ***$p < 0.001$.

Table 4

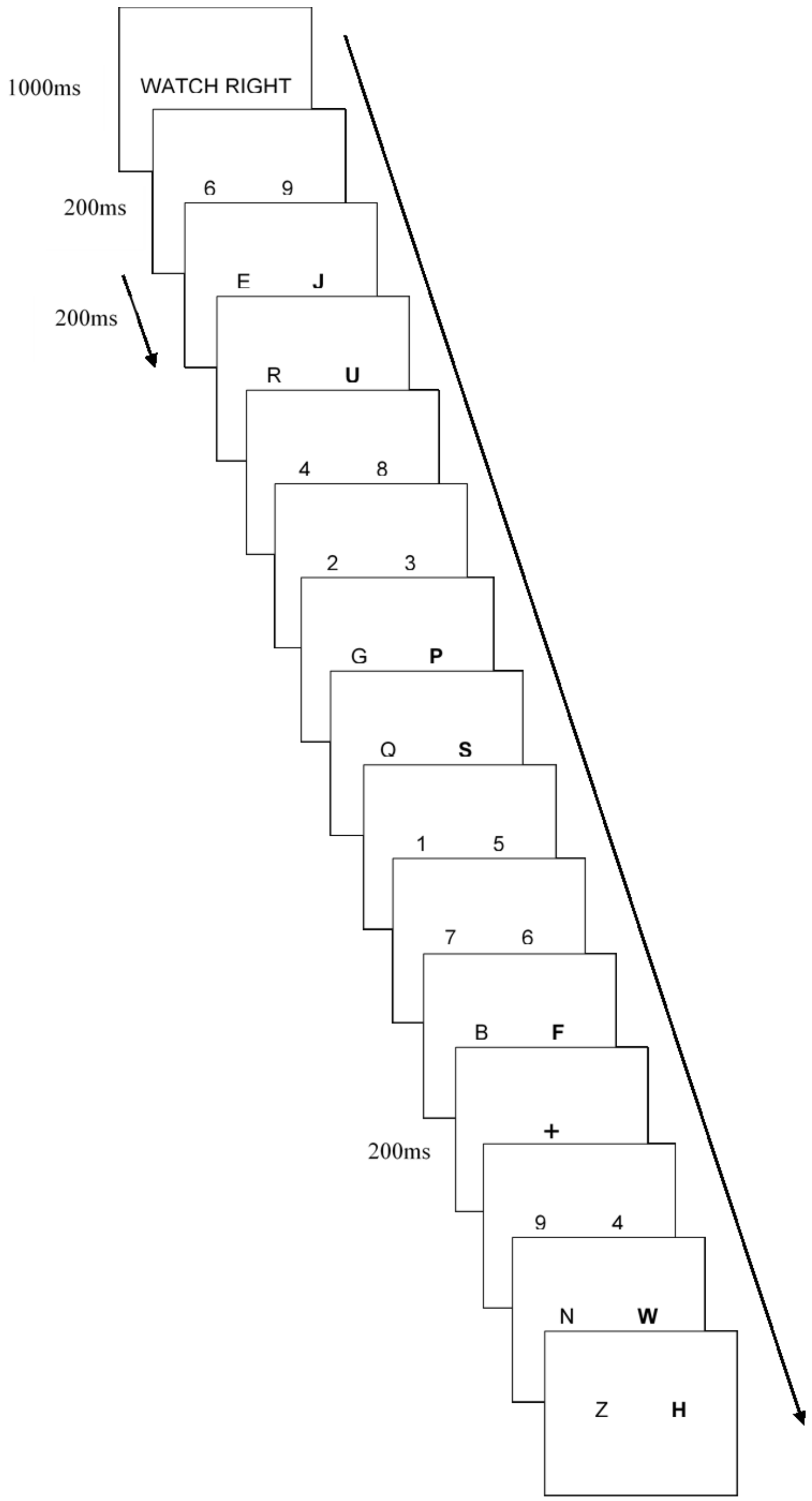
*Means and standard deviations (SD) for the younger and older participants performing the 160ms and 200ms ISIs.*

| | Younger | | | | Older | | | |
|---|---|---|---|---|---|---|---|---|
| | 160ms (N = 21) | | 200ms (N = 22) | | 160ms (N = 22) | | 200ms (N = 24) | |
| | M | SD | M | SD | M | SD | M | SD |
| Age (years) | 21.81 | 4.64 | 21.68 | 3.50 | 73.41 | 7.04 | 67.67 | 4.90 |
| Gender (Male/Female) | 3/18 | | 3/19 | | 10/12 | | 9/15 | |
| Years of full-time education | 15.76 | 3.02 | 16.00 | 2.60 | 16.86 | 2.95 | 15.52 | 3.06 |
| Handedness (L/A/R) | 1/0/20 | | 4/1/17 | | 3/0/19 | | 2/1/21 | |
| ACE-R (max = 100) | 94.25 | 3.80 | 93.80 | 4.89 | 95.91 | 3.15 | 97.06 | 2.62 |
| Fluid Intelligence (IQ) | 116.71 | 15.30 | 120.95 | 16.25 | 98.64 | 15.33 | 98.87 | 13.89 |
| Estimated inspection time (ms) | 36.46 | 8.39 | 37.17 | 9.14 | 68.18 | 14.90 | 68.52 | 16.62 |
| Estimated correct reaction time (ms) | 539.10 | 52.29 | 523.09 | 65.38 | 695.05 | 91.46 | 681.00 | 76.54 |
| Pre-SSI proportion correct | 0.96 | 0.03 | 0.99 | 0.01 | 0.96 | 0.04 | 0.98 | 0.02 |
| MSE score | 0.14 | 0.18 | 0.11 | 0.12 | 0.46 | 0.19 | 0.30 | 0.24 |

L = left, A = ambidextrous, R = right; ACE-R = Addenbrooke's Cognitive Examination-Revised

**Figure Caption**

Figure 1. *An example time-course of a trial from the letter-monitoring task. In the 3-instruction condition participants must: 1) only report letters, 2) follow the FSI, 3) follow the SSI. Targets are shown in bold.*


1000ms
WATCH RIGHT
200ms
6 9
200ms
E J
R U
4 8
2 3
G P
Q S
1 5
7 6
B F
200ms
+
9 4
N W
Z H

**Footnote**

[1]By age-related differences here we refer to the different patterns of processing speed involvement when examining the younger and adult groups separately. As noted earlier, we refrained from making direct comparisons between the age groups, as we originally hypothesized that individual differences should predict the rate of goal neglect regardless of age (see Duncan et al., 2012). As the distributions of both gF and processing speed measures were very different between younger and older adults, we further decided not to include post-hoc age group comparisons. However, as more direct age group comparisons may be of interest to certain readers, analyses that explicitly test the effect of age group are provided in the supplementary material.